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ORIGINAL PAPER

Allometric relationship for estimating above-ground biomass of *Aegialitis rotundifolia* Roxb. of Sundarbans mangrove forest, in Bangladesh

Mohammad Raqibul Hasan Siddique • Mahmood Hossain
Md. Rezaul Karim Chowdhury

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Abstract: Tree biomass plays a key role in sustainable management by providing different aspects of ecosystem. Estimation of above ground biomass by non-destructive means requires the development of allometric equations. Most researchers used DBH (diameter at breast height) and T_H (total height) to develop allometric equation for a tree. Very few species-specific allometric equations are currently available for shrubs to estimate of biomass from measured plant attributes. Therefore, we used some of readily measurable variables to develop allometric equations such as girth at collar-height (G_{CH}) and height of girth measuring point (G_{MH}) with total height (T_H) for *A. rotundifolia,* a mangrove species of Sundarbans of Bangladesh*,* as it is too dwarf to take DBH and too irregular in base to take Girth at a fixed height. Linear, non-linear and logarithmic regression techniques were tried to determine the best regression model to estimate the above-ground biomass of stem, branch and leaf. A total of 186 regression equations were generated from the combination of independent variables. Best fit regression equations were determined by examining co-efficient of determination (R^2), co-efficient of variation (C_V), mean-square of the error (M_{Serror}), residual mean error (R_{sme}), and F-value. Multiple linear regression models showed more efficient over other types of regression equation. The performance of regression equations was increased by inclusion of G_{MH} as an independent variable along with total height and G_{CH}.

Keywords: *Aegialitis rotundifolia*; allometry; biomass; mangroves; sundarbans

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Mohammad Raqibul Hasan Siddique • Mahmood Hossain (✉)
Md. Rezaul Karim Chowdhury
Forestry and Wood Technology Discipline,Khulna University, Khulna -9208, Bangladesh.
E-mail: mahmoodhossain@hotmail.com

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Introduction

Mangroves are distributed in the tropical and subtropical sheltered coastline (Komiyama 2008). The harsh habitat influences the unique processes of primary production and biomass allocation in mangrove forests that differ from terrestrial forests (Toma et al. 1995; Komiyama et al. 2000). Quantity and distribution of vegetal biomass provide important information for ecosystem (Salis et al. 2006), such as forest structure and condition (Westman et al. 1977), forest site productivity and carbon fluxes (Chambers et al. 2001; Cooper 1983; Specht et al. 2003). It is very important to take account of biomass allocation and production of mangroves for having the details of successional changes, nutrient cycling competition among plant communities, site productivity, carbon sequestration and impact of climate change on sustainable management of mangrove forest.

Forest ecologists have developed different methods for biomass estimation (Golley et al. 1975; Komiyama et al. 2008). Of them, area harvest, mean-tree and allometric method are the three popular biomass estimation methods. However, allometric method is frequently used for estimating forest biomass (Golley et al. 1975; Komiyama et al. 2005, 2008; Clough et al. 1989; Clough et al. 1997; Ong et al. 1995, 2004; Tamai et el. 1986). Biomass estimation through allometric models varied greatly among sites (Komiyama et al. 2008; Clough et al. 1989). It is preferable to use species specific and site specific regression models for biomass estimation (Ketterings et al. 2001; Golley et al. 1975). Conversely, the use of generalized equation can lead to a varying proportion of error in biomass estimation for a particular species (Clark et al. 2001; Cairns et al. 2003; Litton et al. 2006; Pilli et al. 2006; Komiyama et al. 2008). *Aegialitis rotundifolia* is a dwarf mangrove and its distribution is limited to the Andaman Island, Orissa and Bangladesh (Kathiresan et al. 2001). In Bangladesh, this species is usually found in coarse textured soil in the strong saline environment of the Sundarbans man-

grove forest (Das et al. 2001). *A. rotundifolia* is less studied species (Saenger 2002) and therefore, knowledge on ecology, stocking and productivity of this species is important for the ecological management and commercial exploitation. The present study aims to derive the allometric models for estimating the above-ground biomass of *A. rotundifolia*, which may contribute to the sustainable management of this species.

Materials and methods

Study area

The study area (N 21°45'03" and E 89°33'11") is bordering the Indian Sundarbans in the West and the Bay of Bengal in the South. Yearly rainfall of the area varies from 1200 to 1500 mm and the average temperature varies from 28°C to 30°C in summer and 18°C to 20°C in winter. The forest is influenced by comparatively higher salinity (2.2%), (Siddique 2001). The vegetation in the study area is dwarf and the average height of the vegetation was about 3–4 m. The major species of this area were *Avicennia alba*, *A. officinalis*, *Xylocarpus granatum*, *X. mekongensis*, *A. rotundifolia*, *Lumnitzera racemosa*, *Rhizophora apiculata*, *R. mucronata*, *Excoecaria agallocha* and *Ceriops decandra* (Sididique 2001).

Sample collecting and processing

Fifty individuals of *A. rotundifolia* were selected (avoiding mechanical and insect damage) with girth (>5 cm to <20 cm) of collar region from its dominated vegetation sites. Total height (T_H) and girth at collar height (G_{CH}) of the selected individuals were measured and recorded. Beside these measurements, height of girth measuring point (G_{MH}) (on an average 0.70 m above from the ground) was also taken because the trunk of this species is conically broad based with gradual tapering towards the apex. Girth, rather than diameter, was used here because the cross-section of the stem is irregular in shape. In such cases, the use of diameter tapes or the division by pi (p) does not give the exact diameter. Moreover, the plant's height was too small (maximum total height 2.89 m and average total height 2.04 m) to take DBH (diameter at breast height) for each stem. After taking these measurements, the individual plants were harvested at the ground level and separated into different parts, such as leaf, branch and stem. All parts of plant were weighed (fresh weight) in the field and sub-samples from each component (about 1 kg) were brought back to the laboratory to get conversion factor (ratio of oven dry weight at 80°C to fresh weight). Oven weights of different parts were calculated from the conversion factor.

Allometric Relationship

Equations of linear, nonlinear and logarithmic regression were used to develop allometric models for predicting above-ground biomass of plant parts (leaves, branches and stems), (Appendix 1). Significant test of regression equations was used by using SAS (6.12) statistical software. The Best fit regression equation was determined by having the highest R^2, with lowest C_V, R_{sme}, M_{Serror}, F-value.

Results

The coefficient of determination (R^2) describes the general fittings of the regression equation for linear relationship between dry weight and fresh weight of different plant parts. The conversion factor yielded a value greater than 0.70. The regression coefficients (b) indicate proportion of organic matter of each plant part. The value ''b'' is equal to the amount of moisture in plant parts. The larger ''b'' value indicates smaller amount of moisture in plant parts. Comparatively values of "b" were decreased for branches, followed by stems and leaves, which indicate a reduction of moisture from green parts to the woody parts of the plant (Table 1).

Table 1. Regressions equation (Y=a+bX) relating dry weights (g) and fresh weights (g) of plant parts

Plant parts	R^2 and p values	a	b	S_a	S_b
Leaf	0.99; p<0.01	0.331	0.352	0.0912	0.009
Branch	0.97; p<0.01	-0.812	0.541	0.412	0.034
Stem	0.95; p<0.01	-2.377	0.523	2.891	0.041

Notes: S_a is standard error of intercept ''a''; S_b is standard error of regression coefficient ''b''.

A total of 186 regression equations (Appendix 1) were used, of which 76 models were excluded for having co-efficient of determination (R^2) value (less than 0.80). The rest of the regression equations were used for evaluating parameters of estimation (R^2, C_V, R_{sme}, M_{Serror} and F).

Most of the selected equations were multiple regressions without transformation of variables. Considering parameters of estimation, the best allometric models (Table 2) are as follows:

$$L = 13.96G_{CH} - 12.38T_H{}^2 - 0.01G_{MH}{}^2 + 0.08G_{CH} \times T_H \times G_{MH} \tag{1}$$

where, L is the leaf biomass, G_{CH} is girth at collar height, T_H is total height, and G_{MH} is the height of girth measuring point.

$$B = 3.09G_{CH}{}^2 - 22.887T_H{}^2 - G_{HM}{}^2 + 0.13G_{CH} \times T_H \times G_{MH} \tag{2}$$

where, B is the branch biomass.

$$S = 3.67G_{CH}{}^2 - 137.16T_H - 0.02G_{MH}{}^2 + 0.12G_{CH} \times T_H{}^2 \times G_{MH} \tag{3}$$

where, S is stem biomass.

$$T = 5.49G_{\mathrm{CH}}^{2} - 251.36T_{\mathrm{H}} - 0.07G_{\mathrm{MH}}^{2} + 0.75G_{\mathrm{CH}} \times T_{\mathrm{H}} \times G_{\mathrm{MH}} \quad (4)$$

where, T is total biomass.

Table 2. Final 5 models for estimating biomass (g) of plant parts

Plant parts	Equation	R^2	Intercept	a	b	c	d	C_V	R_{mse}	M_{Serror}	S_a	S_b	S_c	S_d	F
Leaves	$y=aG_{CH}+bT_H^2+cG_{MH}^2+dG_{CH}T_HG_{MH}$	0.88	-7.96	13.96	-12.38	-0.01	0.08	26.17	37.32	1392.78	10.73	9.22	0.00	0.04	47.13
	$y=aG_{CH}+bT_H+cG_{MH}^2+dG_{CH}T_HG_{MH}$	0.88	38.99	15.62	-53.29	-0.01	0.08	26.32	37.53	1408.37	10.354	43.57	0.00	0.04	46.54
	$y=aG_{CH}^2+bT_H^2+cG_{MH}^2+dG_{CH}T_HG_{MH}$	0.88	72.38	0.57	-13.45	-0.01	0.09	26.49	37.77	1426.83	0.56	9.92	0.00	0.05	45.85
	$y=aG_{CH}^2+bT_H^2+cG_{MH}^2+dG_{CH}T_H^2G_{MH}$	0.87	128.81	0.67	-56.42	-0.01	0.08	26.69	38.06	1449.04	0.55	47.47	0.00	0.05	45.05
	$y=aG_{CH}^2+bT_H^2+cG_{MH}^2+dG_{CH}T_H^2G_{MH}$	0.87	-69.04	24.00	-4.54	-0.01	0.00	26.91	38.37	1472.37	7.72	7.17	0.00	0.00	44.23
Branches	$y=aG_{CH}^2+bT_H^2+cG_{MH}^2+dG_{CH}T_HG_{MH}$	0.92	-103.72	3.09	-22.887	-0.00	0.13	29.848	92.882	8626.982	1.39	24.40	0.02	0.12	69.980
	$y=aG_{CH}^2+bT_H^2+cG_{MH}+dG_{CH}T_HG_{MH}$	0.91	-132.1	3.09	-19.17	0.00	0.11	29.87	92.94	8638.44	1.39	24.95	3.31	0.11	69.88
	$y=aG_{CH}+bT_H^2+cG_{MH}^2+dG_{CH}^2T_HG_{MH}$	0.91	-187.35	3.23	-11.68	1.65	0.00	29.88	92.96	8643.00	1.49	18.26	1.71	0.00	69.84
	$y=aG_{CH}^2+bT_H^2+cG_{MH}^2+dG_{CH}T_H^2G_{MH}$	0.91	-51.12	3.40	-85.73	0.34	0.1	29.91	93.06	8660.82	1.35	118.70	3.07	0.11	69.68
	$y=aG_{CH}^2+bT_H^2+cG_{MH}^2+dG_{CH}T_H^2G_{MH}$	0.91	-142.45	3.32	-51.45	1.78	0.00	29.91	93.08	8664.29	1.44	87.91	1.64	0.00	69.65
Stem	$y=aG_{CH}^2+bT_H+cG_{MH}^2+dG_{CH}T_H^2G_{MH}$	0.95	266.32	3.67	-137.16	-0.02	0.12	17.80	151.20	22862.29	1.47	190.01	0.02	0.04	118.44
	$y=aG_{CH}^2+bT_H+cG_{MH}^2+dG_{CH}T_H^2G_{MH}$	0.95	102.03	3.66	-28.46	-0.02	0.12	17.81	151. 32	22898. 95	1.52	41.12	0.02	0.04	118.25
	$y=aG_{CH}+bT_H+cG_{MH}^2+dG_{CH}T_H^2G_{MH}$	0.95	24.80	71.36	-182.28	-0.02	0.13	17.86	151. 74	23023.60	29.16	179.81	0.02	0.03	117.57
	$y=aG_{CH}^2+bT_H+cG_{MH}+dG_{CH}T_H^2G_{MH}$	0.95	253.39	3.94	-106.13	-2.07	0.11	17.96	152.57	23277.27	1.49	194.78	2.92	0.04	116.22
	$y=aG_{CH}+bT_H^2+cG_{MH}^2+dG_{CH}T_H^2G_{MH}$	0.95	115.99	3.97	-20.24	-2.12	0.11	17.98	152.76	23337.14	1.54	42.26	3.17	0.04	115.90
Total	$y=aG_{CH}^2+bT_H+cG_{MH}^2+dG_{CH}T_HG_{MH}$	0.95	259.51	5.49	-251.36	-0.07	0.75	19.02	247.93	6147104	3.60	309.23	0.05	0.29	115.10
	$y=aG_{CH}^2+bT_H^2+cG_{MH}^2+dG_{CH}T_HG_{MH}$	0.95	-53.52	5.47	-50.58	-0.07	0.77	19.05	248.21	61607.53	3.72	65.21	0.05	0.32	114.83
	$y=aG_{CH}^2+bT_H^2+cG_{MH}^2+dG_{CH}T_H^2G_{MH}$	0.95	-1.55	8.717	-53.95	-0.013	0.15	19.12	249.20	62102.80	2.50	67.72	0.03	0.06	113.86
	$y=aG_{CH}^2+bT_H+cG_{MH}^2+dG_{CH}T_H^2G_{MH}$	0.95	262.87	8.84	-241.94	-0.01	0.14	19.14	249.39	62193.26	2.43	313.40	0.03	0.06	113.69
	$y=aG_{CH}+bT_H^2+cG_{MH}^2+dG_{CH}T_H^2G_{MH}$	0.95	-78.04	9.20	-41.00	-0.77	0.14	19.18	249.95	62473.14	2.53	69.14	5.20	0.06	113.15

Notes: S_a is standard error of intercept "a"; S_b is standard error of regression coefficient "b"; S_c is standard error of regression coefficient "c"; S_d is standard error of regression coefficient "d". $G_{CH}\,T_H\,G_{MH}$ indicated multiplication relationship of G_{CH} with T_H and G_{MH}. The same thing is true for $G_{CH}T_H^2G_{MH}$ and $G_{CH}^2T_HG_{MH}$.

Discussion

In most of the studies, height and DBH were used by regression equations to estimate above-ground biomass of mangrove species (Suzuki et al. 1983; Cintron et al. 1985; Imbert et al. 1989; Lee 1990; Saintilan 1997; Xiao et al. 2004; Cienciala et al. 2006). Mackey (1993) calculated the biomass of individuals using allometric models. However, Komiyama et al. (2002) described that allometric models for estimating stem weight are usually expressed as a function of diameter and height. Girth varies with plant age, architecture and its total height. *A. rotundifolia* is a shrub species with conical broad base, which influenced girth measurement of the species. So, height of girth measuring point (G_{MH}) from the base was considered as an independent parameter which has improved the regression equation.

Allometric models for biomass usually prefer logarithmic transformation (Soares 1997, 2005), but it is not well known as the best estimators (Ong et al. 1980, 1984 and 1985; Cintron et al. 1984, 1985; Amarasinghe et al. 1992a, 1992b; Steinke et al. 1995;; Turner et al. 1995; Fromard et al. 1998, 2004; Ross et al. 2001). Logarithmic transformation guarantees homogeneity of variance (Zar 1968; Payandeh 1981; Sprugel 1983; Brown et al. 1989). Logarithmic transformation deforms the variables, potentially introducing bias in the estimation when we go back to the original unit (Beauchamp et al. 1973; Baskerville 1972). Again, logarithmic transformation does not give the same results as the original nonlinear model does as they are mathematically equivalent but not statistically (Zar 1968; Payandeh 1981). To solve the biased-estimate, Sprugel (1983) developed a correction factor which was supported by Munro (1974), Madgwick et al. (1975), Whittaker et al. (1975). This correction factor is able to reduce approximately 10%–20% of the error of estimation for logarithmic transformation (Sprugel 1983; Baskerville 1972). However, this correction factor did not improve my logarithmic models over multiple regression models.

The selected allometric models to estimate the biomass of different parts of *A. rotundifolia* were multiple regression equations (Table 2). This technique provides some multiple linear models as the best-found estimators. Multiple regression model includes more independent variables that improve the estimation of a dependent variable by decreasing random error and is a good alternative to avoid logarithmic transformation (Wonnacott et al.1980; Payandeh 1981; Ross et al. 2001). Selection of best fit regression equation is the major problem to estimate plant biomass by allometric equation (Whittaker et al. 1969; Brown et al. 1989; Grundy 1995; Steinke et al. 1995; Tam et al. 1995; Mah-

mood et al. 2008). Among the enormous number of multiple regression equations, the best allometric models were selected by considering the values of R^2, C_V, R_{sme}, M_{Serror} and F-value (Table 4). The use of R^2 to select best fit equation was opposed by number of authors (Payandeh 1981; West et al. 1990; Zar 1996). More precise regression equation can be obtained by considering the other parameters of estimation values such as C_V, R_{sme}, M_{Serror} and F-value with R^2 (Schacht et al. 1988; Zak et al. 1989; Busing et al. 1993; Slim et al. 1993; Ibrahima 1995; Zar 1996; Soares et al. 2005). The findings from this study will be useful to assess the present stocking of this species in the Sundarbans mangrove forest for the future management and commercial exploitation in a sustainable way.

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Appendix 1. Regression equations and independent variables for the estimation of biomass

Models	Independent variables
y= a+bX	G_{CH}^2; T_H^2; G_{MH}^2; $G_{CH} T_H$; $G_{CH}^2 T_H$; $G_{CH} T_H^2$; $G_{CH}^2 T_H^2$; $(G_{CH} T_H)^2$; $G_{MH} T_H$; $G_{MH}^2 T_H$; $G_{MH} T_H^2$; $G_{MH}^2 T_H^2$; $(G_{MH} T_H)^2$; $G_{CH} G_{MH}$; $G_{CH}^2 G_{MH}$; $G_{CH} G_{MH}^2$; $G_{CH}^2 G_{MH}^2$; $(G_{CH} G_{MH})^2$; $G_{CH} T_H G_{MH}$; $G_{CH}^2 T_H G_{MH}$; $G_{CH} T_H^2 G_{MH}$; $G_{CH} T_H G_{MH}^2$; $G_{CH}^2 T_H^2 G_{MH}$; $G_{CH}^2 T_H G_{MH}^2$; $G_{CH} T_H^2 G_{MH}^2$; $G_{CH}^2 T_H^2 G_{MH}^2$; $(G_{CH} T_H G_{MH})^2$
$y^{1/3}$= a+b X	G_{CH}^2; T_H^2; G_{MH}^2; $G_{CH} T_H$; $G_{CH}^2 T_H$; $G_{CH} T_H^2$; $G_{CH}^2 T_H^2$; $(G_{CH} T_H)^2$; $G_{MH} T_H$; $G_{MH}^2 T_H$; $G_{MH} T_H^2$; $G_{MH}^2 T_H^2$; $(G_{MH} T_H)^2$; $G_{CH} G_{MH}$; $G_{CH}^2 G_{MH}$; $G_{CH} G_{MH}^2$; $G_{CH}^2 G_{MH}^2$; $(G_{CH} G_{MH})^2$; $G_{CH} T_H G_{MH}$; $G_{CH}^2 T_H G_{MH}$; $G_{CH} T_H^2 G_{MH}$; $G_{CH} T_H G_{MH}^2$; $G_{CH}^2 T_H^2 G_{MH}$; $G_{CH}^2 T_H G_{MH}^2$; $G_{CH} T_H^2 G_{MH}^2$; $G_{CH}^2 T_H^2 G_{MH}^2$; $(G_{CH} T_H G_{MH})^2$
Ln y= Ln a+ b log X	G_{CH}^2; T_H^2; G_{MH}^2; $G_{CH} T_H$; $G_{CH}^2 T_H$; $G_{CH} T_H^2$; $G_{CH}^2 T_H^2$; $(G_{CH} T_H)^2$; $G_{MH} T_H$; $G_{MH}^2 T_H$; $G_{MH} T_H^2$; $G_{MH}^2 T_H^2$; $(G_{MH} T_H)^2$; $G_{CH} G_{MH}$; $G_{CH}^2 G_{MH}$; $G_{CH} G_{MH}^2$; $G_{CH}^2 G_{MH}^2$; $(G_{CH} G_{MH})^2$; $G_{CH} T_H G_{MH}$; $G_{CH}^2 T_H G_{MH}$; $G_{CH} T_H^2 G_{MH}$; $G_{CH} T_H G_{MH}^2$; $G_{CH}^2 T_H^2 G_{MH}$; $G_{CH}^2 T_H G_{MH}^2$; $G_{CH} T_H^2 G_{MH}^2$; $G_{CH}^2 T_H^2 G_{MH}^2$; $(G_{CH} T_H G_{MH})^2$
y= a + b X+ c Y+ d Z	G_{CH}, G_{MH} and T_H; G_{CH}^2, G_{MH} and T_H; G_{CH}, G_{MH}^2 and T_H; G_{CH}, G_{MH} and T_H^2; G_{CH}^2, G_{MH}^2 and T_H; G_{CH}^2, G_{MH} and T_H^2; G_{CH}, G_{MH}^2 and T_H^2; G_{CH}^2, G_{MH}^2 and T_H^2; $G_{CH}^2 G_{MH} T_H$, $G_{CH} G_{MH}^2 T_H$ and $G_{CH} G_{MH} T_H^2$; G_{CH}, T_H and $G_{CH} T_H G_{MH}$; G_{CH}, T_H and $G_{CH}^2 T_H G_{MH}$; G_{CH}, T_H and $G_{CH} T_H^2 G_{MH}$; G_{CH}, T_H and $G_{CH} T_H G_{MH}^2$; G_{CH}, T_H and $G_{CH} T_H^2 G_{MH}^2$; G_{CH}, T_H and $G_{CH}^2 T_H G_{MH}^2$; G_{CH}, T_H and $G_{CH}^2 T_H^2 G_{MH}$; G_{CH}, T_H and $G_{CH}^2 T_H^2 G_{MH}^2$; G_{CH}^2, T_H and $G_{CH} T_H G_{MH}$; G_{CH}^2, T_H and $G_{CH}^2 T_H G_{MH}$; G_{CH}^2, T_H and $G_{CH} T_H^2 G_{MH}$; G_{CH}^2, T_H and $G_{CH} T_H G_{MH}^2$; G_{CH}^2, T_H and $G_{CH} T_H^2 G_{MH}^2$; G_{CH}^2, T_H and $G_{CH}^2 T_H G_{MH}^2$; G_{CH}^2, T_H and $G_{CH}^2 T_H^2 G_{MH}$; G_{CH}^2, T_H and $G_{CH}^2 T_H^2 G_{MH}^2$; G_{CH}, T_H^2 and $G_{CH} T_H G_{MH}$; G_{CH}, T_H^2 and $G_{CH}^2 T_H G_{MH}$; G_{CH}, T_H^2 and $G_{CH} T_H^2 G_{MH}$; G_{CH}, T_H^2 and $G_{CH} T_H G_{MH}^2$; G_{CH}, T_H^2 and $G_{CH} T_H^2 G_{MH}^2$; G_{CH}, T_H^2 and $G_{CH}^2 T_H G_{MH}^2$; G_{CH}, T_H^2 and $G_{CH}^2 T_H^2 G_{MH}$; G_{CH}, T_H^2 and $G_{CH}^2 T_H^2 G_{MH}^2$; G_{CH}^2, T_H^2 and $G_{CH} T_H G_{MH}$; G_{CH}^2, T_H^2 and $G_{CH}^2 T_H G_{MH}$; G_{CH}^2, T_H^2 and $G_{CH} T_H^2 G_{MH}$; G_{CH}^2, T_H^2 and $G_{CH} T_H G_{MH}^2$; G_{CH}^2, T_H^2 and $G_{CH} T_H^2 G_{MH}^2$; G_{CH}^2, T_H^2 and $G_{CH}^2 T_H G_{MH}^2$; G_{CH}^2, T_H^2 and $G_{CH}^2 T_H^2 G_{MH}$; G_{CH}^2, T_H^2 and $G_{CH}^2 T_H^2 G_{MH}^2$; G_{CH}^2, T_H^2 and $G_{CH}^2 T_H G_{MH}$; $(G_{CH} T_H)^2$, $G_{CH}^2 T_H$ and $G_{CH}^2 G_{MH} T_H$; G_{CH}^2, $G_{CH} T_H$ and $G_{CH}^2 G_{MH} T_H$; G_{CH}^2, $(G_{CH} T_H)^2$ and $G_{CH}^2 G_{MH} T_H$; G_{CH}^2, $(G_{CH} T_H)^2$ and $G_{CH}^2 T_H$; G_{CH}, T_H and $G_{CH} T_H$; $(G_{CH} T_H)$, $G_{CH}^2 T_H$ and G_{MH}^2; $(G_{CH} T_H)$, $G_{CH} G_{MH}$ and $G_{MH} T_H$; $(G_{CH} T_H)$, $G_{CH} G_{MH}$, T_H and $G_{CH} G_{MH} T_H$;
y= a + b X + c Y+ d Z+ e W	G_{CH}, T_H, G_{MH} and $G_{CH}^2 T_H G_{MH}$; G_{CH}, T_H, G_{MH} and $G_{CH} T_H^2 G_{MH}$; G_{CH}, T_H, G_{MH} and $G_{CH} T_H G_{MH}^2$; G_{CH}, T_H, G_{MH} and $G_{CH}^2 T_H^2 G_{MH}$; G_{CH}, T_H, G_{MH} and $G_{CH}^2 T_H G_{MH}^2$; G_{CH}, T_H, G_{MH} and $G_{CH} T_H^2 G_{MH}^2$; G_{CH}, T_H, G_{MH} and $G_{CH}^2 T_H^2 G_{MH}^2$; G_{CH}^2, T_H, G_{MH} and $G_{CH}^2 T_H G_{MH}$; G_{CH}^2, T_H, G_{MH} and $G_{CH} T_H^2 G_{MH}$; G_{CH}^2, T_H, G_{MH} and $G_{CH} T_H G_{MH}^2$; G_{CH}^2, T_H, G_{MH} and $G_{CH}^2 T_H^2 G_{MH}$; G_{CH}^2, T_H, G_{MH} and $G_{CH}^2 T_H G_{MH}^2$; G_{CH}^2, T_H, G_{MH} and $G_{CH} T_H^2 G_{MH}^2$; G_{CH}^2, T_H, G_{MH} and $G_{CH}^2 T_H^2 G_{MH}^2$; G_{CH}, T_H^2, G_{MH} and $G_{CH}^2 T_H G_{MH}$; G_{CH}, T_H^2, G_{MH} and $G_{CH} T_H^2 G_{MH}$; G_{CH}, T_H^2, G_{MH} and $G_{CH} T_H G_{MH}^2$; G_{CH}, T_H^2, G_{MH} and $G_{CH}^2 T_H^2 G_{MH}$; G_{CH}, T_H^2, G_{MH} and $G_{CH}^2 T_H G_{MH}^2$; G_{CH}, T_H^2, G_{MH} and $G_{CH} T_H^2 G_{MH}^2$; G_{CH}, T_H^2, G_{MH} and $G_{CH}^2 T_H^2 G_{MH}^2$; G_{CH}, T_H, G_{MH}^2 and $G_{CH}^2 T_H G_{MH}$; G_{CH}, T_H, G_{MH}^2 and $G_{CH} T_H^2 G_{MH}$; G_{CH}, T_H, G_{MH}^2 and $G_{CH} T_H G_{MH}^2$; G_{CH}, T_H, G_{MH}^2 and $G_{CH}^2 T_H^2 G_{MH}$; G_{CH}, T_H, G_{MH}^2 and $G_{CH}^2 T_H G_{MH}^2$; G_{CH}, T_H, G_{MH}^2 and $G_{CH} T_H^2 G_{MH}^2$; G_{CH}, T_H, G_{MH}^2 and $G_{CH}^2 T_H^2 G_{MH}^2$; G_{CH}^2, T_H^2, G_{MH} and $G_{CH}^2 T_H G_{MH}$; G_{CH}^2, T_H^2, G_{MH} and $G_{CH} T_H^2 G_{MH}$; G_{CH}^2, T_H^2, G_{MH} and $G_{CH} T_H G_{MH}^2$; G_{CH}^2, T_H^2, G_{MH} and $G_{CH}^2 T_H^2 G_{MH}$; G_{CH}^2, T_H^2, G_{MH} and $G_{CH}^2 T_H G_{MH}^2$; G_{CH}^2, T_H^2, G_{MH} and $G_{CH} T_H^2 G_{MH}^2$; G_{CH}^2, T_H^2, G_{MH} and $G_{CH}^2 T_H^2 G_{MH}^2$; G_{CH}^2, T_H, G_{MH}^2 and $G_{CH}^2 T_H G_{MH}$; G_{CH}^2, T_H, G_{MH}^2 and $G_{CH} T_H^2 G_{MH}$; G_{CH}^2, T_H, G_{MH}^2 and $G_{CH} T_H G_{MH}^2$; G_{CH}^2, T_H, G_{MH}^2 and $G_{CH}^2 T_H^2 G_{MH}$; G_{CH}^2, T_H, G_{MH}^2 and $G_{CH}^2 T_H G_{MH}^2$; G_{CH}^2, T_H, G_{MH}^2 and $G_{CH} T_H^2 G_{MH}^2$; G_{CH}^2, T_H, G_{MH}^2 and $G_{CH}^2 T_H^2 G_{MH}^2$; G_{CH}, T_H^2, G_{MH}^2 and $G_{CH}^2 T_H G_{MH}$; G_{CH}, T_H^2, G_{MH}^2 and $G_{CH} T_H^2 G_{MH}$; G_{CH}, T_H^2, G_{MH}^2 and $G_{CH} T_H G_{MH}^2$; G_{CH}, T_H^2, G_{MH}^2 and $G_{CH}^2 T_H^2 G_{MH}$; G_{CH}, T_H^2, G_{MH}^2 and $G_{CH}^2 T_H G_{MH}^2$; G_{CH}, T_H^2, G_{MH}^2 and $G_{CH} T_H^2 G_{MH}^2$; G_{CH}, T_H^2, G_{MH}^2 and $G_{CH}^2 T_H^2 G_{MH}^2$; G_{CH}^2, T_H^2, G_{MH}^2 and $G_{CH}^2 T_H G_{MH}$; G_{CH}^2, T_H^2, G_{MH}^2 and $G_{CH} T_H^2 G_{MH}$; G_{CH}^2, T_H^2, G_{MH}^2 and $G_{CH} T_H G_{MH}^2$; G_{CH}^2, T_H^2, G_{MH}^2 and $G_{CH}^2 T_H^2 G_{MH}$; G_{CH}^2, T_H^2, G_{MH}^2 and $G_{CH}^2 T_H G_{MH}^2$; G_{CH}^2, T_H^2, G_{MH}^2 and $G_{CH} T_H^2 G_{MH}^2$; G_{CH}^2, T_H^2, G_{MH}^2 and $G_{CH}^2 T_H^2 G_{MH}^2$;

Notes: y is dependent variable biomass; a, b, c, d are constants; X, Y, Z and W are independent variables G_{CH}, T_H and G_{MH}, where G_{CH} is girth at collar height; T_H is total height; G_{MH} is height of girth measuring point. $G_{CH} T_H$ indicated multiplication relationship of G_{CH} with T_H. The same thing is true for $G_{CH}^2 T_H^2$, $G_{MH} T_H$, $G_{MH}^2 T_H$, and $G_{CH}^2 T_H^2$, etc.